Large Eddy Simulation of Sediment Transport in the Presence of Surface Gravity Waves, Currents and Complex Bedforms

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LONG-TERM GOAL

Our long-term goal is to develop numerical simulation techniques for generating accurate predictions of sediment transport in the coastal zone.

OBJECTIVES

Our current main focus is building upon earlier work that produced quantitatively accurate hydrodynamics and producing a tool for sediment transport modeling. Our tool is a large-eddy simulation [LES] in three dimensions and time, at scales on the order of meters, and in the presence of waves and a current. Our numerical analysis objectives include accurate representation of the flow near rough boundaries, creation of improved models for the unresolved or sub-filter scale [SFS] motions and sediment transport, and optimization of the computer code for multiprocessor computer systems.

APPROACH

The numerical simulation code employed in our simulations solves the unsteady Navier-Stokes equations with the Boussinesq approximation and in three dimensions. An advection-diffusion equation [with a subfilter-scale closure] is used to represent suspended sediment. The subfilter-scale Reynolds stress and sediment flux are modeled in terms of resolved quantities with models that have no adjustable or tunable constants and yet which have been shown to incorporate the essential features needed for a correct subfilter-scale parameterization. These equations are discretized with second-order differences and solved with a fractional-step or projection method.

An oscillatory, periodic pressure gradient has been implemented in the code to model flow motions caused by waves. Other planned modifications to the code will account for some of the sediment-fluid interactions. Stratification effects will be included and a hindered settling velocity may be implemented. Eventually, the code may model multiple size classes of sediment.

Our major challenges involved in extending the code to field scales arise from boundary layer regions that form in the flow, e.g., in the wake of ripples. Our approach is to model the wall effect via an assumed rough-wall velocity profile. Fortunately, Cederwall and Street (1999) have demonstrated that sophisticated subfilter-scale models can be used successfully , together with rather simple models of a rough wall, a LES of an incompressible, atmospheric-boundary-layer. This gave us a good starting

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point. Katopodes, Street & Ferziger (2000a&b) have developed, for the interior of the flow, a subfilter-scale model that includes all of the important physics to the desired order of accuracy. See also Street (1999). [Note that we employ the term subfilter-scale to mean the unresolved motions; these are often called the subgrid-scale [SGS] motions].

Once the code has been verified for large-scale flows with rough boundaries, it will be used to model field-scale flow. We are collaborating with investigators who have conducted experiments at SandyDuck and using the simulation code to simulate experimental conditions for comparison with the experimental results.

WORK COMPLETED

The discovery of the significant influence of vortices on the sediment transport led us to focus on that issue and we have produced two publications [Zedler & Street, 2000a and 2000b] related to that subject.

An oscillatory, periodic pressure-gradient was implemented in the code to model flow motions caused by waves in the presence of currents. A test case was run to confirm that our code would perform properly when an unsteady/oscillating pressure gradient was used. The comparison was to the Kawamura, et al. (1999) direct numerical simulation of oscillatory channel flow in the presence of a mean current. We did a LES of their case with our code and compared the mean velocities at different phases of the pressure gradient. Although we did not optimize our gridding or do any grid-independence tests, our results are in reasonable agreement with those of the Kawamura et al., both in profile shape and magnitude. Accordingly, we have completed the development of this capability.

Another major challenge is involved in extending the code to field scales both because the Reynolds number is large and because the bed at field scale is essentially rough [so one must model the near-bed behavior]. As shown below, we have extended the simulation scale, but have not yet implemented the rough-wall boundary condition.

RESULTS

In the laboratory-scale simulations of Zedler and Street, there is a strong coupling between the sediment and fluid motions in flows over the bedforms. Over both boundary configurations [straight ripples and three-dimensional ripples], there is a clear correlation between regions where the velocity motions have a significant vertical component and the presence of sediment concentrations that are high relative to ambient values. As a first step in the effort to simulate field scales, we scaled up the domain and adjusted the pressure gradient to produce the desired mean velocity. Thus, the simulation in progress, for which early results are shown below, uses our LES code with a no-slip bottom boundary condition [making the boundary-condition approach comparable to that of Scandura, et al. (2000)], who did a DNS. Bradford (2000) and Jensen, et al. (1999) also have employed the no-slip boundary condition with RANS codes and turbulence models. Here we are using it in a LES with a dynamic-mixed subfilter-scale [SFS] model.

Our code is being used to simulate channel flow over field-scale ripples with a Reynolds number of over 600,000. The ripples are straight-crested with a wavelength of 2.25 meters and amplitude of 0.1125 m, such that their height to length ratio is 1:10. The computational domain contains two ripples, is 4.5 m L x 0.65 m H x 1.0 m W, and has been resolved by 162 x 82 x 50 grid points. The grid is

stretched in the vertical with exponential stretching; the first grid point is located 100 wall-units from the bed. The flow is driven by a pressure gradient. It generates a maximum streamwise velocity of roughly 1 m/s. This pressure gradient value was calculated using nonlinear wave theory because the code will be used to simulate wave effects (by oscillating the pressure gradient) once the channel flow has reached a statistically steady state.

The early results are promising. Although the flow has not yet reached a statistically steady state, it has run for almost twelve seconds (real time) and is showing the same types of structure seen in the much smaller scale flows. Figure 1 shows an instantaneous snapshot of the total velocity vectors plotted on the center plane at 6.5 s. The flow near the top of the channel is nearly uniform and reaches a maximum speed of 0.9 m/s. The speed decreases near the bed. A recirculation zone is present in the trough. This general pattern is ubiquitous across the channel width and is what we expect based on our smaller-scale-flow simulations.

However, we know that the flow over ripples is unstable to perturbations, so one expects the development of Görtler-type vortex structures. Figure 2 shows the velocity vectors in the plane perpendicular to the main flow direction (with the streamwise velocity filtered out) on a cross-stream plane just downstream of the ripple crest at the location of the arrow in Figure 1. Two streamwise vortices have formed to either side of the center plane. They originated just downstream of the ripple crest and have lifted off the bottom to the height shown in Figure 2. Figures 3a and 3b show magnified pictures of the recirculation zones that form on the center plane (Figure 3a) and about a quarter of the distance across the channel (Figure 3b). A comparison reveals that the recirculation zone penetrates higher into the channel at the cross-stream location of the vortex (Figure 3b) than it does at the cross-stream location of the center plane (Figure 3a). Thus, the vortices, which form in the flow, significantly affect the structure of the recirculation zone and as in the cases examined in Zedler, et al. (2000a&b), sediment transport will depend strongly on these structures. Figure 4 shows the further evolution of the flow structures at 11.7 s. It remains to be seen what the effect is of accounting for the rough boundary; this is our next step. It is probable that the rough boundary will slow the flow, but we do not expect that the basic large-scale structure of the vortices will be affected significantly.

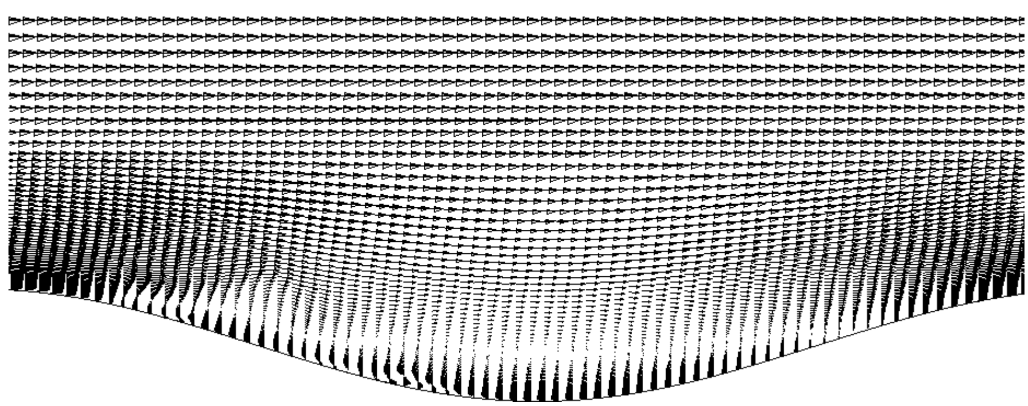

Figure 1. Velocity Vectors plotted on the channel center plane at time = 6.5 s. The cross-section plot in Figure 2 is located approximately halfway between the trough and the left crest. Reynolds number ~ 640,000.

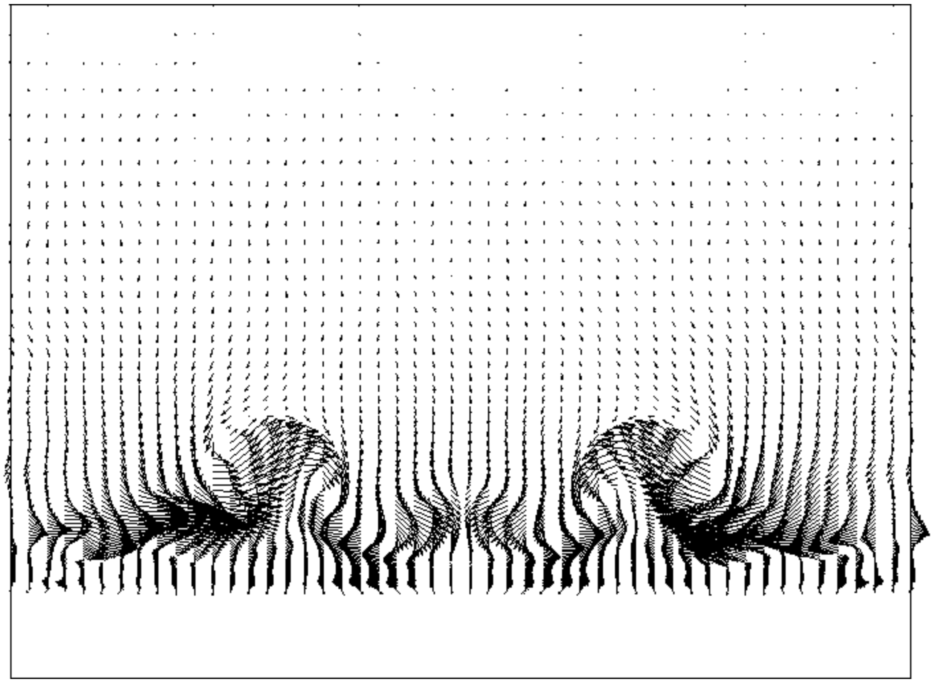

Figure 2. The y-z component of the instantaneous velocity vectors in the plane perpendicular to the direction of the main flow. This illustrates the formation of two streamwise vortices, on either side of the center plane.

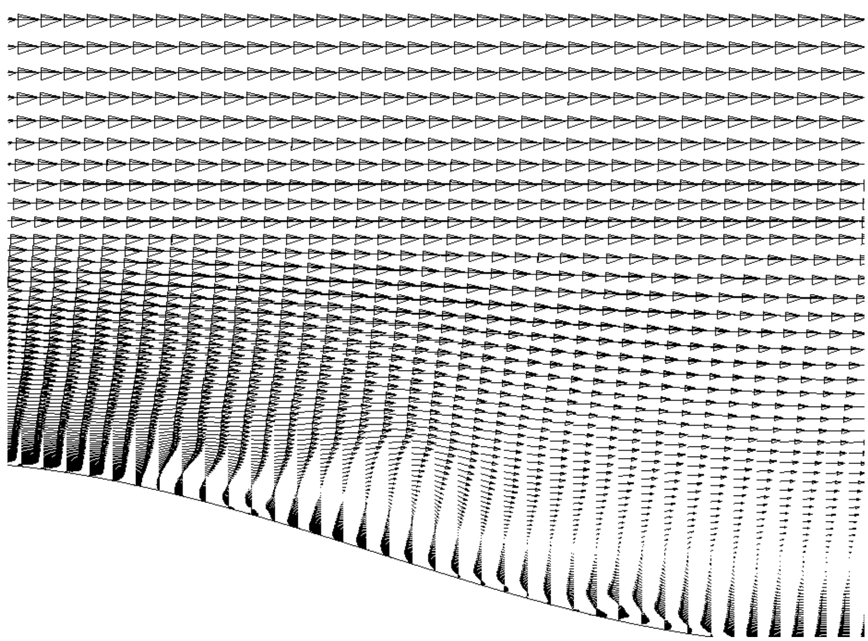

Figure 3a. Instantaneous velocity vectors on the channel center plane. This is a blown-up version of Figure 1.

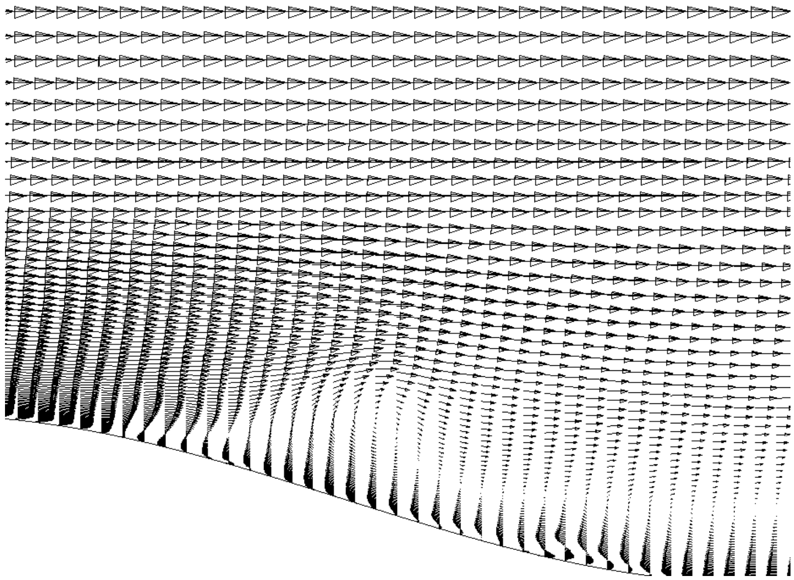

Figure 3b. Instantaneous velocity vectors on a plane at the cross-stream location of the left vortex in Figure 2. It is notable that the recirculation zone rises much higher in the flow at this cross-stream location. Its highest point is at the location of the streamwise vortex (Figure 2).

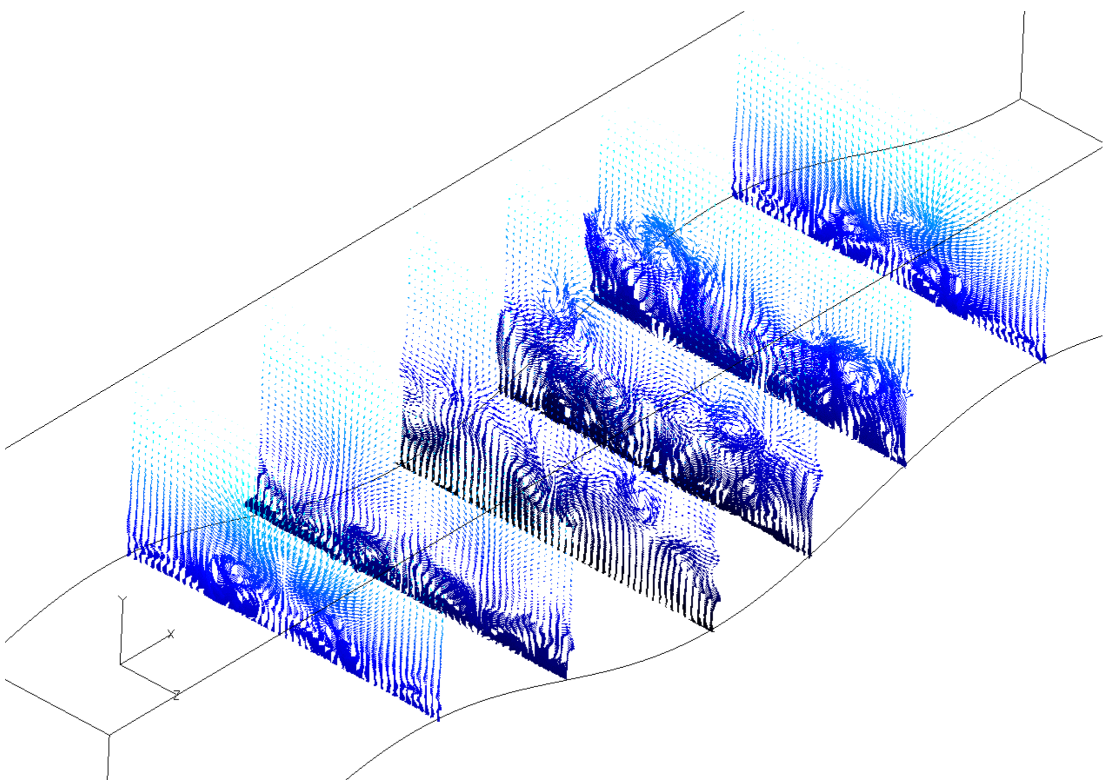

Figure 4. Overview of flow at 11.7 s. Plot shows the vectors in the planes perpendicular to the flow direction at various locations along the channel. Plots are colored according to height above the bed to illustrate vertical locations of structures. Reynolds number ~ 660,000.

IMPACT/APPLICATION

Large-eddy simulations calculate the time evolution of the resolved motions in the flow and are an important tool for studying the relationship between sediment transport patterns and coherent structures, such as bursts and sweeps that form in the flow. We have already demonstrated the value of a LES in understanding and visualizing the flow physics and sediment transport in Zedler and Street (2000 a & b). We are now extending our large-eddy simulations to larger scales. Recent developments in subfilter-scale modeling techniques allow the full fluctuating velocities in the flow to be described as a function of the resolved-scale velocities [so-called velocity estimation models]. These estimation models then are used to produce the subfilter-scale Reynolds stress and transport flux terms. We will implement these new models as well [see Katopodes, Street & Ferziger (2000a&b)]. These models, as well as the model used to date, have no adjustable or tunable constants that must be set *a priori*. The ultimate results of this study should both illustrate the importance of coherent structures on sediment transport and lead to development of a predictive capability for flows at the scale of the SandyDuck nearshore measurements.

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